Chapter 1
Energy and Cogeneration

1.1 Introduction

1.1.1 Energy Concept

The word energy is derived from the Greek *in* (in) and *ergon* (work). The accepted scientific energy concept has been used to reveal the common characteristics in diverse processes where a particular type of work is produced. At the most basic level, the diversity in energy forms can be limited to four: kinetics, gravitational, electric, and nuclear.

Energy is susceptible to being transformed from one form to another, where the total quantity of energy remains unchanged; it is known that: "Energy can neither be created nor destroyed, only transformed". This principle is known as the first law of thermodynamics, which establishes an energy balance in the different transformation processes.

When the energy changes from one form to another, the energy obtained at the end of the process will never be larger than the energy used at the beginning, there will always be a defined quantity of energy that could not be transformed.

The relationship of useful energy with energy required for a specific transformation is known as conversion efficiency, expressed in percent. This gives origin to the second law of the thermodynamics, which postulates that the generation of work requires a thermodynamic potential (temperature, pressure, electric charges, *etc.*) between two energy sources, where energy flows from the highest potential to the lowest, in which process there is a certain amount of energy that is not available for recovery. In general, the second law establishes the maximum quantity of energy possible that one can obtain in a transformation process, through the concept of exergetic efficiency.

The energy is the motor of humanity's social, economic, and technological development, and it has been the base for the different stages of development of society: (1) the primitive society whose energy was based on its own human ener-

gy and on the consumption of gathered foods, (2) the society of hunters, which had a nomadic character, based on the use of the combustion of the wood, (3) the primitive agricultural society, which consumed wood and used animal traction, (4) the advanced agricultural society, which consumed wood, energy derived from water and wind, and some coal and animal traction, (5) the industrial society, which consumed coal (for vapor production), wood, and some petroleum, and finally (6) the technological society, which consumes petroleum (especially for machines of internal combustion), coal, gas, and nuclear energy.

Current society depends for the most part on the energy resources derived from petroleum and due to its character of finite, high costs and problems of contamination, the energy resources should be diversified, with priority toward the renewable ones, depending on the characteristic of each country and region.

The energy at the present time is intimately related to aspects such as saving and efficient use, economy, economic and social development, and the environment, which should be analyzed in order to establish an appropriate energy politics to assure the energy supply and therefore the necessary economic growth.

1.1.2 Energy and Its Impacts

1.1.2.1 Energy and Development

In the relationship between energy and development, the consumptions of primary energy in the world, and regions, the tendencies, as well as external trade and prices are analyzed. Concerning the perspectives, the energy reserves, the modifications in the production structure, and the modifications in consumption and prices are studied.

An important aspect to consider is the analysis of the relationship between energy and development through the relationship between the energy consumption and the gross domestic product (GDP) of a country. On the one hand, the GDP is representative of the level of economic life, and on the other, it is indicative of the level of the population's life and therefore of the degree of personal well-being reached. The economic activity and the well-being imply energy consumption; in the first case, the energy would be an intermediate goods of consumption that is used in the productive processes in order to obtain goods and services, in the second case, a final goods of consumption for the satisfaction of personal necessities, such as cooking and conservation of food, illumination, transport, air conditioning, *etc*.

For a particular country, the relationship that exists among the total consumption of primary energy *per* year in a given moment, generally evaluated in equivalent tons of petroleum (ETP) and the GDP, evaluated in constant currency, gives an idea of the role of energy in the economic activity. The relationships are called energy intensity of the GDP, energy content of the GDP, or energy coefficient. However, it is verified that such a quotient is at the same time very variable, so

much in the time for a country in particular, as in the space in a given moment if several countries are considered – even if they have comparable levels of economic development. This is not only completed at macroeconomic level but also for a sector or specific economic branch.

In general, both variations of the energy intensity are strongly determined by two types of factors: (1) factors that concern the national economic structure, as the nature or percentage of participation of the economic activities that compose the GDP; this is because the energy consumption for units of product is very diverse depending on the sector of the economy (agriculture, industry, transport, services, *etc.*); and (2) technological factors that refer to the type of energy technology consumed and the form used by each industry, economic sector, or consumer.

The participation of the energy sector in the GDP is usually low, although in some countries strong petroleum producers for export will spread to become bigger, with consideration of the following aspects: (1) energy availability is a necessary condition, although not sufficient for the development of economic activity and the population's well-being. (2) The energy sector is, at least potentially, one of the motors of the industrial and technological development of the country, since it is the most important national plaintiff of capital goods, inputs, and services. (3) Import requirements, and therefore of foreign currencies, are a function of the degree of integration with the productive sector. (4) To be a capital-intensive sector, it competes strongly with others in the assignment of resources. (5) Moreover, since energy projects have a very long period of maturation, equipment not used to its capacity produces restrictions and important costs in the economic activity, while an oversupply would mean a substantial deviation of unproductive funds that could be used by another sector. (6) The increasing and increasingly important participation of the energy sector in the government's fiscal revenues.

1.1.2.2 Energy and Economy

The energy analysis should not only consider the technical and political aspects, but also the economic one. From an economic point of view, energy satisfies the necessities of the final consumers and of the productive apparatus, which includes the energy sector. To arrive to the consumer it is necessary to continue by a chain of economic processes of production and distribution. These processes and the companies that carry out and administer them, configure the energy sector, being key in the economy, because it is a sector with a strong added value, very intensive in capital and technology, with an important weight in external trade, both in the producing countries as consumers of energy and in public finances.

For these characteristics the energy sector is susceptible to exercising multiple macroeconomic effects, through its investments, of the employment and added value that it generates, of the taxes that it pays or it makes people pay for its products, which produces numerous inter-industrial effects, since energy is an intermediate consumption of all branches of economic activity.

The economic analysis has three basic focuses: microeconomic, macroeconomic, and international relationships, with particular theoretical and methodological principles considering the specificities of the energy sector. The microeconomic analysis is based on economic calculation in the energy sector and administration of public energy companies. This includes (1) prices and costs of energy resources, (2) problems of the theory of the value, (3) internal prices, tarification systems and policies, (4) analysis of energy consumption and its determinants, (5) public companies and problems of energy investments, (6) evaluation of the energy projects, and (7) some alternative lines of analysis.

In macroeconomic analysis energy is considered in relation to the economic growth problem, through the perspective of planning. The central topics are: (1) energy and factors and global production functions, (2) energy and economic growth; analysis instruments and main evolutions, (3) macroeconomic implications of the evolution of prices, for example of petroleum, the question of the surplus and its use, and (4) macroeconomics, energy modeling, and planning.

In the case of international relationships, the mains topics for the study of main phenomena and energy processes are: (1) the main actors of energy scene, (2) the nature of markets and energy industries and their recent restructuring, and (3) the determination of international energy prices.

The insurance of the best selection of investment projects is an important aspect of the economic calculation, and methods that assure the attainment and treatment of data relative to the alternative projects are necessary. Data includes information on definition and project cost estimation, on definition and estimate of benefits and advantages of the project, and on relationships and interdependences that affect or will be affected by the projects. The treatment of these data makes the measurement, evaluation, and comparison of the economic results of alternative projects possible.

With respect to the macronomics of energy, there is much interesting work in the field of modeling, mainly in as concerns analysis of the demand, in connection with the evolution of economic activity and diverse technological and social factors. The econometrics method allows one to obtain: (1) a detailed analysis of the energy demand in the level of energy uses, (2) a calculation of the final energy for each type of use, whereas the necessities of useful energy derived from, technical-economic and social indicators, (3) a construction of scenarios to take into account the evolution of all non-estimated factors or those whose evolution is bound to political, economic, or energy options, and (4) a consideration of the scenarios in terms of useful and final energy and an extension of the macroeconomic models to better represent the energy demand.

1.1.2.3 Energy Savings and Efficient Use of Energy

Energy conservation refers to all those conducive actions taken to achieve a more effective use of finite energy resources. This includes rationalization of the use of energy by means of elimination of current waste and an increase in the efficiency

in the use of energy. This is achieved by reducing specific energy consumption, without sacrificing the quality of life and using all possibilities to do this, even substituting one energy form for another. The objective of energy conservation is to optimize the global relationship between energy consumption and economic growth.

It is clear that there exists the possibility of sustaining an economic growth process with a smaller consumption of energy, or in other words, energy resources can be used more efficiently by applying measures that are attainable from the economic point of view, especially with high prices of energy, and are acceptable and even convenient from the ecological point of view.

Energy conservation can be generally achieved in three stages. The first stage corresponds to the elimination of energy waste, which can be achieved with minimum investment, using existent facilities appropriately. The second level corresponds to the modification of existent facilities to improve their energy efficiency. The third stage corresponds to the development of new technologies that can enable less energy consumption *per* unit of produced product.

Energy conservation can be considered an alternative source of energy, since its implementation allows reduction of the energy consumption necessary for a certain activity, without implying a reduction of the economic activity or of the quality of life.

Two examples of technologies are of special interest from the point of view of more efficient use of energy: the combined use of electric power and heat, called cogeneration, and obtaining thermal energy at a relatively low degree by means of the use of a smaller amount of energy of a higher degree, using a heat pump. There are many technologies that can be applied to energy conservation in various sectors, including transport, industry, commercial and residential, among others.

In order to develop economic studies of different strategies of energy conservation, the costs of the saving of a certain quantity of energy obtained by means of the conservation measures are compared with the cost of the energy that would be necessary should these conservation measures not be carried out.

1.1.2.4 Energy and the Environment

Another important aspect to consider is the relationship between energy consumption and preservation of the environment. Energy use is essential to satisfy human necessities. These necessities change substantially with time and humanity evolved parallel to the moderate growth of its energy consumption until the Industrial Revolution and with an actual growing energy consumption. The speed and amplitude of this development, as well as accumulative effects lead to surpassing certain limits that this consumption pattern imposes on industrial civilization endanger human survival and that of the Earth. For the first time in history, human activity can destroy the fragile essential ecological balance necessary for life reproduction, and polluting waste perturbs the cycle of bio-geo-chemicals and the risks of occurrence of accidents with massive consequences increases continuously.

The main environmental risks are intimately associated with the increase in energy consumption and derive from carbonic anhydride emissions, nitrogen oxides and sulfur, methane, chlorofluorocarbons (CFC), acid rain, greenhouse gases, *etc*., or the risk of accidents of spills of petroleum on land and in the sea and accidents in nuclear reactors. Moreover, the elimination of the problems of residual products and of dismantling of the reactors after their useful life and the dangers of contamination associated with the use of the nuclear energy in general are further environmental risks.

The engineering proposals will be sustained in an appropriate use of energy in order to mitigate the noxious effects of the polluting residues of energy resources, mainly those of petrochemical origin.

1.1.2.5 Energy Policy

The establishment of an energy policy where various political actions are analyzed, and where norms, financial outlines, institutions, and technologies necessary to achieve a sustainable development are given, is very important. Among the main aspects to consider in the energy policy in order to ensure sustainable development are (1) to promote the preservation and improvement of environment, (2) to incorporate in the political constitution the necessary precepts that regulate the use and conservation of energy resources (mainly the renewable ones), (3) to make transparent the costs of the different energies, (4) to implant norms in order to regulate energy markets to assure a diversity of primary sources in the medium term, (5) to establish a bank of energy information of public character, and (6) to carry out a strategic plan that considers long-term energy perspectives.

The policy of sustainable development should: allow a global vision of human activities, consider the bond between energy consumption and environmental contamination, consider cultural and geographic diversity, evaluate the carried out efforts justly, foresee what is possible to do in the future, and be sustained on solid scientific and technical bases. The energy policy should also consider the abundant resources of renewable energy resources that have a smaller environmental impact.

Concerning the climatic change problem, it will be possible to achieve a reduction in the emission of greenhouse gases by means of two main actions that will be feasible in the medium and the long term. The first one is to sequestrate very important amounts of these gases by means, for instance, of preservation and incrementation of forest areas. The second, it is to take advantage of renewable energy sources. This last option has solid technological routes that lead to the proposed goal.

It is clear that there is a necessity for a complete revision of the technical and economic potentials of renewable energy resources to be able to make more precise decisions of energy politics regarding energy and the environment, which can lead towards a sustainable development.

1.2 Overview of World Energy

1.2.1 World Primary Energy Production and Consumption

The International Energy Annual (2006) presents information and trends on world energy production and consumption of petroleum, natural gas, coal, and electricity, and carbon dioxide emissions from the consumption and flaring of fossil fuels.

Between 1996 and 2006, the world's total output of primary energy petroleum, natural gas, coal, and electric power (hydro, nuclear, geothermal, solar, wind, and biomass) increased at an average annual rate of 2.3 %.

In 2006, petroleum (crude oil and natural gas plant liquids) continued to be the world's most important primary energy source, accounting for 35.9 % of world primary energy production. During the 1996 and 2006 period, petroleum production increased by 11.7 million barrels *per* day, or 16.9 %, rising from 69.5 to 81.3 million barrels *per* day. Coal was the second primary energy source in 2006, accounting for 27.4 % of world primary energy production. World coal production totaled 6.8 billion short tons. Natural gas, the third primary energy source, accounted for 22.8 % of world primary energy production in 2006. Production of dry natural gas was 3 trillion m^3.

Hydro, nuclear, and other (geothermal, solar, wind, and wood and waste) electric power generation ranked fourth, fifth, and sixth, respectively, as primary energy sources in 2006, accounting for 6.3, 5.9, and 1.0 %, respectively, of world primary energy production. Together they accounted for a combined total of 6.1 trillion kWh.

In 2006, the US, China, and Russia were the leading producers and consumers of world energy. These three countries produced 41 % and consumed 43 % of the world's total energy. The US, China, Russia, Saudi Arabia, and Canada were the world's five largest producers of energy in 2006, supplying 50.3 % of the world's total energy. Iran, India, Australia, Mexico, and Norway together supplied an additional 12.2 % of the world's total energy.

The US, China, Russia, Japan, and India were the world's five largest consumers of primary energy in 2006, accounting for 51.8 % of world energy consumption. They were followed by Germany, Canada, France, the UK, and Brazil, which together accounted for an additional 12.6 % of world energy consumption

1.2.1.1 Petroleum

Saudi Arabia, Russia, and the US were the largest producers of petroleum in 2006. Together, they produced 33.3 % of the world's petroleum. Production from Iran and Mexico accounted for an additional 9.6 %. In 2006, the US consumed 20.7 million barrels *per* day of petroleum (24 % of world consumption). China and Japan were second and third in consumption, with 7.2 and 5.2 million barrels *per* day, respectively, followed by Russia and Germany.

1.2.1.2 Natural Gas

World production of dry natural gas increased by 0.6 trillion m^3, or at an average annual rate of 2.4 %, over the period from 1996 to 2006. Russia was the leading producer in 2006 with 0.66 trillion m^3, followed by the US with 0.53 trillion m^3. Together these two countries produced 40 % of the world's total. Canada was third in production with 0.18 trillion m^3, followed by Iran and Norway, with 0.10 and 0.09 trillion m^3, respectively. These three countries accounted for 13 % of the world total.

In 2006, the US, which was the leading consumer of dry natural gas at 0.62 trillion m^3, and Russia, second at 0.47 trillion m^3, together accounted for 37 % of world consumption. Iran ranked third in consumption, with 0.11 trillion m^3, followed by Germany and Canada, at 0.10 and 0.94 trillion m^3, respectively.

1.2.1.3 Coal

Coal production increased by 1.7 billion short tons between 1996 and 2006, or at an average annual rate of 2.9 %. China was the leading producer in 2006 at 2.6 billion short tons. The US was the second leading producer in 2006 with 1.2 billion short tons. India ranked third with 499 million short tons, followed by Australia with 420 million short tons and Russia with 323 million short tons. Together these five countries accounted for 74 % of world coal production in 2006.

China was also the largest consumer of coal in 2006, using 2.6 billion short tons, followed by the US with a consumption of 1.1 billion short tons; India, Germany, and Russia together accounted for 71 % of world coal consumption.

1.2.1.4 Hydroelectric Power

Between 1996 and 2006 hydroelectric power generation increased by 503 billion kWh at an average annual rate of 1.9 %. China, Canada, Brazil, the US, and Russia were the five largest producers of hydroelectric power in 2006. Their combined hydroelectric power generation accounted for 39 % of the world total. China led the world with 431 billion kWh, Canada was second with 352 billion kWh, Brazil was third with 345 billion kWh, and the US was fourth with 289 billion kWh, followed by Russia with 174 billion kWh.

1.2.1.5 Nuclear Electric Power

Nuclear electric power generation increased by 369 billion kWh between 1996 and 2006, or at an average annual rate of 1.5 %. The US led the world in nuclear electric power generation in 2006 with 787 billion kWh, France was second with 428 billion kWh, and Japan third with 288 billion kWh. In 2006, these three countries generated

57 % of the world's nuclear electric power. Russia, China, and India accounted for almost two-thirds of the projected net increment in world nuclear power capacity between 2003 and 2005. In the reference case, Russia contributed 18 GW of nuclear capacity between 2003 and 2005, India 17 GW, and China 45 GW. Several OECD nations with existing nuclear programs also added new capacity, including South Korea with 14 GW, Japan with 11 GW, and Canada with 6 GW. The recent construction of new plants in the United States has added 16.6 GW.

1.2.1.6 Geothermal, Solar, Wind, and Wood and Waste Electric Power

Geothermal, solar, wind, and wood and waste electric generation power increased by 237 billion kWh between 1996 and 2006, at an average annual rate of 8.8 %. The US led the world in geothermal, solar, wind and wood and waste electric power generation in 2006 with 110 billion kWh, Germany was second with 52 billion kWh, followed by Spain with 27 billion kWh, Japan with 26 billion kWh, and Brazil with 17 billion kWh. These five countries accounted for 52 % of the world geothermal, solar, wind, and wood and waste electric power generation in 2006.

1.2.2 Energy Consumption by the End-use Sector

The different kinds of energies used in residential, commercial, and industrial sectors vary widely regionally, depending on a combination of regional factors, such as the availability of energy resources, the level of economic development, and political, social, and demographic factors (IEA 2006).

1.2.2.1 The Residential Sector

Energy use in the residential sector accounts for about 15 % of worldwide delivered energy consumption and is consumed by households, excluding transportation uses. For residential buildings, the physical size of structure is one indication of the amount of energy used by its occupants. Larger homes require more energy to provide heating, air conditioning, and lighting, and they tend to include more energy-using appliances. Smaller structures require less energy because they contain less space to be heated or cooled and typically have fewer occupants. The types and amounts of energy used by households vary from country to country, depending on the natural resources, climate, available energy infrastructure, and income levels.

1.2.2.2 The Commercial Sector

The need for services such as health, education, financial and government services increases as populations increase. The commercial sector, or services sector, con-

sists of many different types of buildings. A wide range of service activities are included, such as, schools, stores, restaurants, hotels, hospitals, museums, office buildings, banks, etc. Most commercial energy use occurs through supply services such as space heating, water heating, lighting, cooking, and cooling. Energy consumed for services not associated with buildings, such as for traffic lights and city water and sewer services, is also included as commercial sector energy use. Economic growth also determines the degree to which additional activities are offered and utilized in the commercial sector.

Slow population growth in most industrialized countries contributes to slower rates of increase in the commercial energy demand. In addition, continued efficiency improvements are projected to moderate the growth of energy demand, as energy-using equipment is replaced with newer equipment. Conversely, strong economic growth is expected to include continued growth in business activity, with its associated energy use. Among the industrialized countries, the US is the largest consumer of commercially delivered energy.

1.2.2.3 The Industrial Sector

The industrial sector include a very diverse group of industries as manufacturing, agriculture, mining and construction, and a wide range of activities, such as process and assembly uses, space conditioning, and lighting. Industrial sector energy demand varies across regions and countries, based on the level of economic activity, technological development, and population, among other factors. Industrialized economies generally have more energy-efficient industry than non-industrialized countries, whose economies generally have higher industrial energy consumption relative to the GDP. On average, the ratio is almost 40 % higher in non-industrialized countries (UN 2008).

1.2.2.4 The Transportation Sector

Energy use in the transportation sector includes the energy consumed in moving people and goods by road, rail, air, water, and pipeline. The road transport component includes light-duty vehicles, such as automobiles, sport utility vehicles, small trucks, and motorbikes, as well as heavy-duty vehicles, such as large trucks used for moving freight and buses for passenger travel. Growth in economic activity and population are the key factors that determine transportation sector energy demand. Economic growth spurs increased industrial output, which requires the movement of raw materials to manufacturing sites, as well as movement of manufactured goods to end users.

A primary factor contributing to the expected increase in energy demand for transportation is the steadily increasing demand for personal travel in both non-industrialized and industrialized economies. Increases in urbanization and personal incomes have contributed to increases in air travel and to increased motorization

(more vehicles) in the growing economies. For freight transportation, trucking is expected to lead the growth in demand for transportation fuel. In addition, as trade among countries increases, the volume of freight transported by air and marine vessels is expected to increase rapidly over the projection period.

1.2.3 World Carbon Dioxide Emissions

Total world carbon dioxide (CO_2) emissions from the consumption of petroleum, natural gas, and coal, and the flaring of natural gas increased from 22.8 billion metric tons of carbon dioxide in 1996 to 29.2 billion metric tons in 2006, or by 28.0 %. The average annual growth rate of carbon dioxide emissions over the period was 2.5 % (China, the US, Russia, India, and Japan were the largest sources of carbon dioxide emissions from the consumption and flaring of fossil fuels in 2006, producing 55 % of the world total). The next five leading producers of carbon dioxide emissions from the consumption and flaring of fossil fuels were Germany, Canada, the UK, South Korea, and Iran, and together they produced an additional 10 % of the world total. In 2006, China's total carbon dioxide emissions from the consumption and flaring of fossil fuels were 6.0 billion metric tons of carbon dioxide, about 2 % more than the 5.9 billion metric tons produced by the US. Russia produced 1.7 billion metric tons, India 1.3 billion metric tons, and Japan 1.2 billion metric tons.

In 2006, the consumption of coal was the world's largest source of carbon dioxide emissions from the consumption and flaring of fossil fuels, accounting for 41.3 % of the total. World CO_2 emissions from the consumption of coal totaled 12.1 billion metric tons of carbon dioxide in 2006, up 42 % from the 1996 level of 8.5 billion metric tons. China and the US were the two largest producers of (CO_2) from the consumption of coal in 2006, accounting for 41 and 18 %, respectively, of the world total. India, Japan, and Russia together accounted for an additional 14 %.

Petroleum was the second source of carbon dioxide emissions from the consumption and flaring of fossil fuels in 2006, accounting for 38.4 % of the total. Between 1996 and 2006 emissions from the consumption of petroleum increased by 1.6 billion metric tons of carbon dioxide, or 17 %, rising from 9.6 to 11.2 billion metric tons. The US was the largest producer of CO_2 from the consumption of petroleum in 2006 and accounted for 23 % of the world total. China was the second largest producer, followed by Japan, Russia, and Germany, and together these four countries accounted for an additional 21 %.

Carbon dioxide emissions from the consumption and flaring of natural gas accounted for the remaining 20.2 % of CO_2 carbon dioxide emissions from the consumption and flaring of fossil fuels in 2006. Emissions from the consumption and flaring of natural gas increased from 4.7 billion metric tons of carbon dioxide in 1996 to 5.9 billion metric tons in 2006, or by 25 %. The US and Russia were the two largest producers of carbon dioxide from the consumption and flaring of natural gas in 2006 accounting for 20 and 15 %, respectively, of the world total. Iran, Japan, and Germany together accounted for an additional 10 %.

1.2.4 Energy Perspectives

World energy consumption is expected to expand by 50 % in the next 20 years. World energy consumption will continue to increase strongly as a result of robust economic growth and expanding populations in the world's developing countries. Energy demand in industrialized countries is expected to grow slowly, at an average annual rate of 0.7 %, whereas energy consumption in the emerging economies of non-industrialized countries is expected to expand by 2.5 % *per* year. Given expectations that world oil prices will remain relatively high throughout the projection, liquid fuels are the world's slowest growing source of energy; the consumption of liquids increases at an average annual rate of 1.2 %. Projected high prices for oil and natural gas, as well as rising concerns about the environmental impacts of fossil fuel use, improve the prospects for renewable energy sources. Worldwide, coal consumption is projected to increase by 2.0 % *per* year. The cost of coal is comparatively low relative to the cost of liquids and natural gas, and abundant resources in large energy-consuming countries (including China, India, and the US) make coal an economical fuel choice. The projected coal consumption decrease in the majority of industrialized countries is due to either the slow growth rate of coal, the electricity demand growth being slow, and natural gas, nuclear power, and renewable being likely to be used for electricity generation rather than coal. Although liquid fuels and other petroleum products are expected to remain important sources of energy, natural gas remains an important fuel for electricity generation worldwide because it is more efficient and less carbon intensive than other fossil fuels. The use of hydroelectricity and other grid-connected renewable energy sources continues to expand, with consumption projected to increase by 2.1 % *per* year.

Natural gas and coal, which are currently are the fastest growing fuel sources for electricity generation worldwide, continue to lead the increase in fuel use in the electric power sector. The strongest growth in electricity generation is projected for non-industrialized countries, increasing by 4.0 %, as rising standards of living increase the demand for home appliances and the expansion of commercial services, including hospitals, office buildings, *etc.* In industrialized nations, where infrastructures are well established and population growth is relatively slow, a much slower growth in generation is expected, *i.e.*, 1.3 %.

Because natural gas is an efficient fuel for electric power generation and produces less carbon dioxide than coal or petroleum products, it is an attractive choice in many nations.

Rising fossil fuel prices, energy security, and greenhouse gas emissions support the development of new nuclear energy generating capacities. Most expansion of installed nuclear power capacity is expected in non-industrialized countries.

There is still considerable uncertainty about the future of nuclear power, however, and a number of issues may slow the development of new nuclear power plants. Plant safety, radioactive waste disposal, and the proliferation of nuclear weapons, which continue to raise public concerns in many countries, may hinder

plans for new installations, and high capital and maintenance costs may keep some countries from expanding their nuclear power programs.

Renewable fuels are the fastest growing source of energy. Higher fossil fuel prices, particularly for natural gas in the electric power sector, along with government policies and programs supporting renewable energy, allow renewable fuels to compete economically. The use of hydroelectricity and other grid-connected renewable energy sources continues to expand, with consumption projected to increase by an average of 2.1 % *per* year. Much of the growth in renewable energy consumption is projected to come from mid-scale to large-scale hydroelectric facilities in non-industrialized countries. Most of the increase in renewable energy consumption in industrialized countries is expected to come from non-hydroelectric resources, such as wind, solar, geothermal, municipal solid waste, and biomass. The European Union (EU) has set a target of increasing the renewable energy share to 20 % of gross domestic energy consumption by 2020, including a mandatory minimum of 10 % for bio fuels. Most EU member countries offer incentives for renewable energy production, including subsidies and grants for capital investments and premium prices for generation from renewable sources. Installation of wind-powered generating capacity has been particularly successful in Germany and Spain.

1.3 Air Conditioning Needs

Environmental conditions play an important role in the development of human activities. The relationship between humidity, temperature and wind velocity should create particular conditions on physiological well-being, which depends on the geographic location, specific activity, and in many cases, on cultural, social, and economic factors. Outside this area of well-being, it will be required in particular for each case of heating or cooling, the elimination or addition of humidity, as well as a control of the velocity of the air.

Man has created his own habitat to protect himself against inclement weather, where structures and appropriate building materials must be used, as well as adequate clothing. Throughout history mankind has responded to the air conditioning problem by means of vernacular architecture, using available materials that have allowed conservation or dissipation of thermal energy, reducing the requirements of conventional refrigeration.

Population growth, emigration toward urban zones, abandonment of agricultural activity, changes in design and in construction materials and architectural structures have contributed to the creation of microclimates where important effects have been had on the augmentation of temperature, humidity and in modifications of the patterns of the wind.

The abuse of the use of materials with high thermal inertia, the indiscriminate use of glass like structural material, where to avoid the introduction of solar radiation – filters have been placed that diminish brightness and increase electricity

consumption for illumination – the absence of natural ventilation, among other things, have increased the temperature in the interior of rooms. Another factor has been the increase of the electric equipment in the interior, computers and their peripherals, fans, coffee, and a great diversity of appliances that dissipate heat, which is reinstated to the interior.

The external factors, such as the amount of gases and vapors of water, products of the combustion of hydrocarbons, and in the transport and industrial sectors, the greenhouse gases emission (global heating) and the decrease of ozone gas in the stratospheric atmosphere layer due to the emission of certain refrigerants have caused increases of temperature in certain regions of the world, with alarming consequences, such as an increase in pluvial precipitation, thaw, *etc*. It is also necessary to mention the climatic changes originated by desertification and the increase of the use of soil for agricultural and urban purposes. Additionally an inadequate handling of air conditioning facilities has resulted in inadequate operation and bigger energy consumption.

All of the above-mentioned factors have caused an important increase in the requirement of cooling, of refrigeration, and air conditioning, which are highly intensive in electricity with more than 15 % of what is generated in the whole world.

In order to diminish the energy requirements for air conditioning, very diverse strategies exist, among them, from the industrial point of view, efficient equipment production and the integration of appropriate, environmentally-friendly refrigerants. In the domestic and services sectors, for example, new equipment, thermal isolation of walls and roofs, decrease in the heat generated to the interior by various domestic electric appliances, and a more appropriate handling of air conditioning systems.

Another strategy consists of the diversification of the use of the conventional systems of refrigeration, based on mechanical compression, to other cooling methods based on the use of thermal energy, such as the sorption refrigeration cycles in its different processes and configurations.

Sorption refrigeration systems such as absorption and adsorption ones operate with thermal energy of a low level of temperature (90–200 °C), derived from the use of thermal solar energy conversion, the waste heat of industrial and agricultural activities, biogas combustion, among thermal sources. There exists a great potential in the recovery of dissipated heat from fuel cells, in particular the proton exchange membrane type, which promises to be an energy technology with big perspectives and where it is possible to obtain a cogeneration process where electric power and refrigeration generation is simultaneous using the energy dissipated by their own fuel cell for the thermal operation of air conditioning system.

1.4 Cogeneration Systems

Today, energy is perhaps the driving force of most economies in the world. Electric power is essential for lighting and operating equipment and appliances used in

commercial, institutional, and industrial facilities. Conventional generation contributes to two-thirds of all fuel used to make electricity, which is generally wasted by venting unused thermal energy from power generation equipment into the air or discharging it into water streams.

Cogeneration can be defined as the simultaneous production of electric power and useful heat from the burning of a single fuel. This technique of combined heat and power production has been applied successfully in industrial and tertiary sectors; the energy resources are used more efficiently, which creates opportunities for reductions in both purchased energy costs and in environmental impact. This occurs mainly because of efficient technology levels and the guarantee of available electricity and low level environmental impact.

Integrated systems for combined heat and power significantly increase efficiency of energy utilization, up to 80 %, by using thermal energy from power generation equipment for cooling, heating, and humidity control systems. Figure 1.1 shows that a typical cogeneration system can reduce energy requirements by close to 20 % compared to separate production of heat and power. For 170 units of input fuel, the cogeneration system converts 130 units to useful energy of which 50 units are electricity and 80 units are for steam or hot water. Traditional separate heat and power components require 215 units of energy to accomplish the same end use tasks.

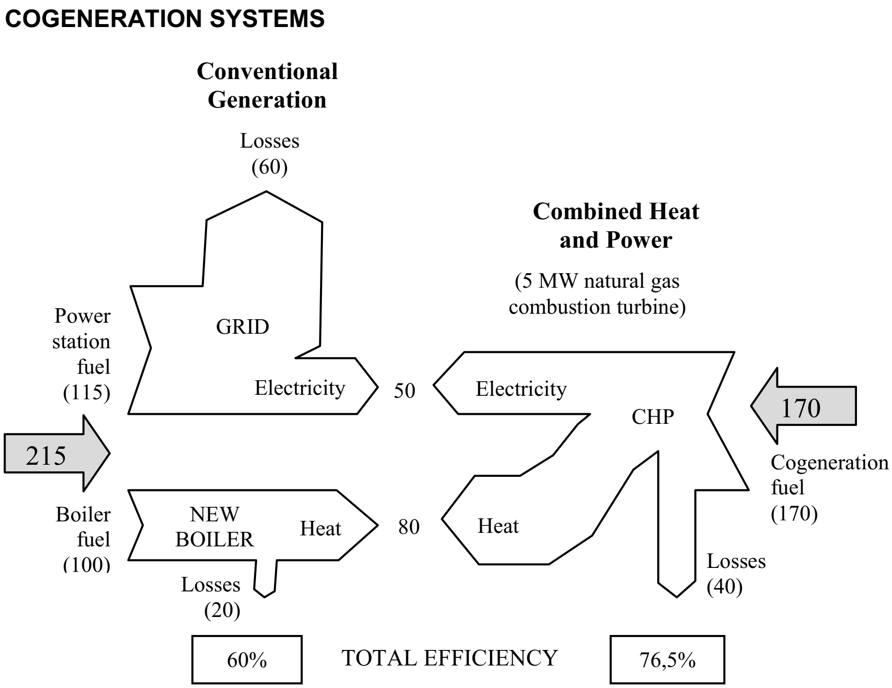

Figure 1.1 Example of CHP energy savings (IEA 2006)

A cogeneration system has the potential to dramatically reduce industrial sector carbon and air pollutant emissions and increase source energy efficiency. Industrial applications of cogeneration systems have been around for decades, producing electricity and by-product thermal energy onsite, and converting 75 % or more of the input fuel into useable energy. Typically, cogeneration systems operate by generating hot water or steam from the recovered waste heat and using it for process heating, but it also can be directed to an absorption chiller where it can provide process or space cooling. These applications are also known as cooling, heating, and power (CHP).

1.4.1 Centralized versus Distributed Power Generation

The traditional model of electric power generation and delivery is based on the construction of large, centrally-located power plants. "Central" means that a power plant is located on a hub surrounded by major electrical load centers. For instance, a power plant may be located close to a city to serve the electrical loads in the city and its suburbs or a plant may be located at the midpoint of a triangle formed by three cities.

Power must be transferred from a centrally-located plant to the users. This transfer is accomplished through an electricity grid that consists of high-voltage transmission systems and low-voltage distribution systems. High-voltage transmission systems carry electricity from the power plants to sub-stations. At the substations, the high-voltage electricity is transformed into low-voltage electricity and distributed to individual customers.

Inefficiencies are associated with the traditional method of electric power generation and delivery. Figure 1.2 illustrates the losses inherent to the generation and delivery of electric power in traditional centralized power plants and in distributed power plants.

Traditional power plants convert about 30 % of the fuel's available energy into electric power, and highly efficient, distributed power plants convert over 50 % of available energy into electric power (Hardy 2003). The majority of the energy content of the fuel is lost at the power plant through the discharge of waste heat. Further energy losses occur in the transmission and distribution of electric power to the individual user. Inefficiencies and pollution issues associated with conventional power plants provide the impetus for new developments in "onsite and near-site" power generation.

The traditional structure of the electrical utility market has resulted in a relatively small number of electric utilities. However, current technology permits development of smaller, less expensive power plants, bringing in new, independent producers. Competition from these independent producers along with the re-thinking of existing regulations has affected the conventional structure of electric utilities.

The restructuring of the electric utility industry and the development of new "onsite and near-site" power generation technologies have opened up new possi-

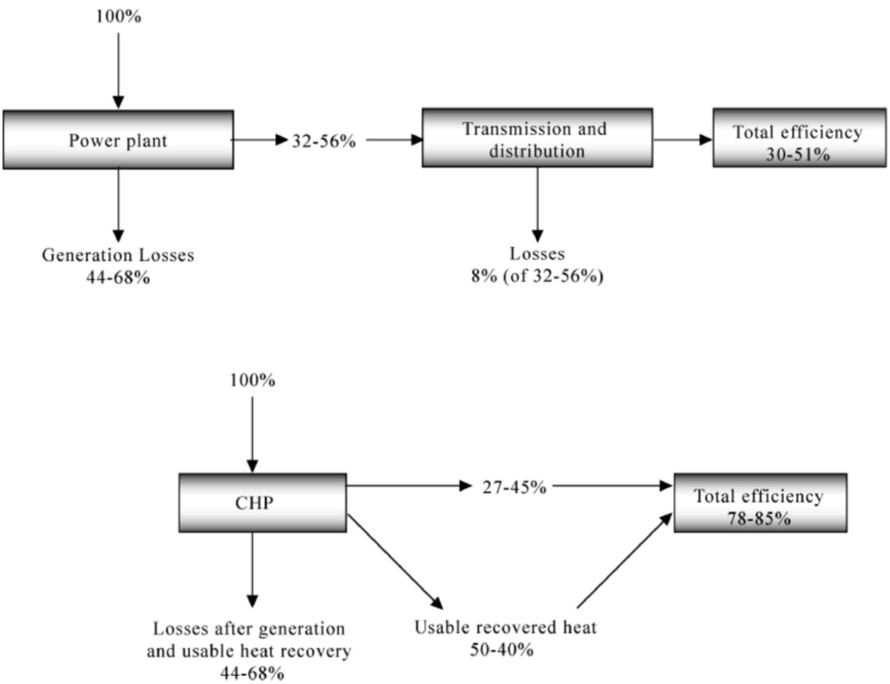

Figure 1.2 Centralized *versus* distributed power generation

bilities for commercial, public, industrial facilities, building complexes, and communities to generate and sell power. Competitive forces have created new challenges as well as opportunities for companies that can anticipate technological needs and emerging market trends.

Distributed power generation using cogeneration systems has the potential to reduce carbon and air pollutant emissions and to increase resource energy efficiency dramatically. Cogeneration systems produce both electric or shaft power and useable thermal energy onsite or near site, converting as much as 80 % of the fuel into useable energy. A higher efficiency in energy conversion means that less fuel is necessary to meet energy demands. Also, onsite power generation reduces the load on the existing electricity grid, resulting in better power quality and reliability. Additionally, cogeneration systems include values such as variable fuel requirements, enhanced energy-security, and improved indoor air quality.

1.4.2 Cogeneration Technologies

Cogeneration systems utilizing internal combustion engines (Otto and Diesel versions), steam turbines, and gas turbines in open cycle are the most utilized technologies worldwide. However, some emerging technologies have become current

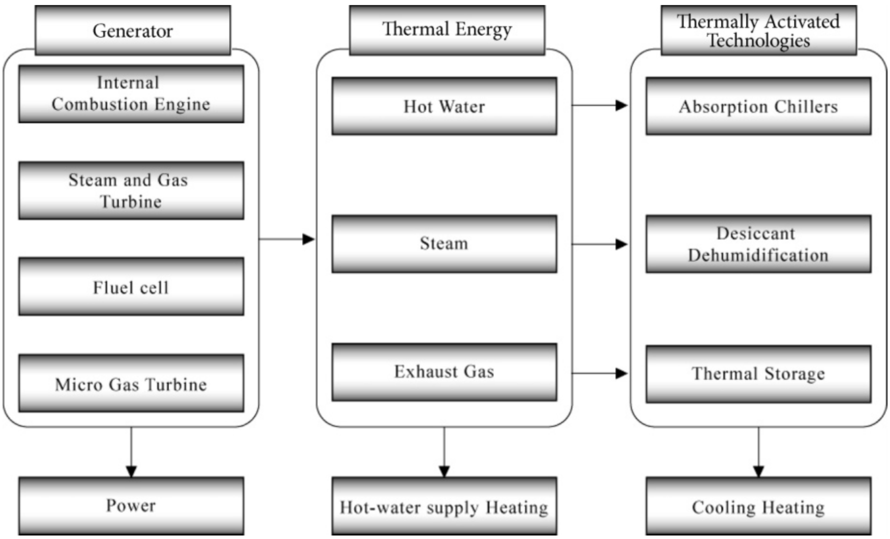

Figure 1.3 Cogeneration technologies

applications, *e.g.*, micro gas turbines in closed cycles and fuel cell systems (see Figure 1.3).

The most often cogeneration systems encountered are a gas turbine generator or reciprocating engine generator coupled with a waste heat recovery boiler, or a steam boiler coupled with a steam turbine generator. The main difference between the two types of systems is the order in which the electricity is obtained. The gas turbine and reciprocating engine first produce electricity, then the hot exhaust gases are sent to the waste heat boiler to generate steam, a process known as a topping cycle. When a boiler produces steam first and then some (or all) of that steam is sent to a steam turbine to generate electricity, the process is considered a bottoming cycle.

Depending upon the nature of the installation using these cogeneration systems, each has its advantages. The gas turbine and reciprocating engine systems are much better for new installations. The amount of power produced for a given heat demand is superior to that of the boiler/steam turbine system. For retrofit applications, where a boiler is already installed and running, the steam turbine may be ideally suited. Many installations generate steam at a higher pressure than necessary then throttle the steam to a lower pressure before it is sent to process. Replacing the pressure reducing valve with a steam turbine recovers the energy wasted in the throttling process and converts it to electricity. Moreover, since steam turbines are relatively inexpensive, the first cost is minimal.

The main advantage of operating fuel cells in a cogeneration mode is that the system consumes less fuel than would be required to produce the same thermal and electrical energy in separate processes, because of efficient technology levels. The guarantee of the available electricity and low level environmental impacts are further advantages (Rosen 1990).

Table 1.1 Waste heat characteristics of power generation technologies (Onsite Sycom 1999)

	Usable temp. for co-generation (°C)	Cogeneration output (J/kWh)	Uses for heat recovery
Diesel engine	80–500	3,400	Hot water, LP steam, district heating
Natural gas engine	150–250	1,000–5,000	Hot water, LP steam, district heating
Gas turbine	250–600	3,400–12,000	Direct heat, hot water, LP-HP steam, district heating
Micro-turbine	200–350	4,000–15,000	Direct heat, hot water, LP steam
Fuel cell	60–370	500–3,700	Hot water, LP steam

LP: low pressure, HP: high pressure

1.4.3 Heat Recovery in Cogeneration Systems

Electrical and shaft power generation efficiencies have attained maximum values of 50 % for internal combustion engines, 60 % for combustion turbines (combined cycle), 30 % for micro gas turbines, and 70 % for fuel cells (Onsite Sycom 1999). Most power generation components falling into these categories do not reach the upper level efficiencies of these technologies. Components such as micro gas turbines that convert 30 % of the input fuel into electrical or shaft power fail to harness 70 % of the available energy source. Energy that is not converted to electrical power or shaft power is typically rejected from the process in the form of waste heat. The task of converting waste heat to useful energy is called heat recovery and is primarily accomplished through the use of heat exchanger devices such as heat recovery steam generators (HRSG), water heaters, or air heaters.

The characteristics of waste heat generated in combustion turbines, internal combustion engines, and fuel cells directly affect the efficacy with which useful energy is recovered for additional processes. Some of the characteristics of the waste heat generated by these power generation technologies are presented in Table 1.1.

Waste heat is typically produced in the form of hot exhaust gases, process steam, and process liquids/solids. In combustion turbines and internal combustion engines, heat is rejected in the combustion exhaust and the coolant. Fuel cells reject heat in the form of hot water or steam.

We can classify recovered heat as low-temperature (< 230 °C), medium temperature (230–650 °C), or high-temperature (> 650 °C) (Shah 1997). Recovered heat that is utilized in the power generation process is internal heat recovery, and recovered heat that is used for other processes is external heat recovery. Combustion pre-heaters, turbochargers, and recuperators are examples of internal heat recovery components. Heat recovery steam generators, absorption chillers, and desiccant systems are examples of external heat recovery components.

1.4.4 Cogeneration System Selections

Normally, cogeneration applications are geared to accomplishing two loads: an electrical load and a thermal one. Too often this load following results in difficulties in both sizing and operation of the cogeneration equipment, and limits the operational capacity of this equipment to the smallest load to be followed. Therefore, the potential savings of a cogeneration system, as related to its capacity, is restricted to this smallest load.

One the most important factors affecting the choice is the magnitude of each type of load, both thermal and electrical (see Table 1.2). If either of these is relatively low, or even non-existent, then a cogeneration system is obviously not an option. In most cases, no thermal load exists. Only in the rarest of circumstances would it be economically feasible to generate power while not recovering any thermal energy. If it does appear that pure power generation is an economic possibility, a detailed study of the power company rate structure that serves the facility should be performed. It is likely that changing to another rate structure would lower electrical costs enough to make the pure power generation option economically undesirable.

Another criterion is the size of the electrical and thermal loads relative to each other. This should not be confused with the first criteria. We are assuming that the magnitude of each type of load is sufficient to consider a cogeneration system. For high electrical usage *vs*. thermal usage, a system with a higher electrical efficiency is desirable, for example, a reciprocating engine generator. If the opposite is true, the thermal load outpaces the electrical load, and then a steam turbine would better suit the application. Finally, if both are relatively equal, then a gas turbine system might be the initial system to analyze.

The relative magnitudes of the thermal and electrical loads are not the only criteria, but also the time dependent nature of each load. Loads that vary considerably with respect to time can cause undesirable effects on certain systems, much

Table 1.2 Classifications of cogeneration systems by size range (http://www.chpcentermw.org/presentations/WI-Focus-on-Energy-Presentation-05212003.pdf)

Systems designation	Size range	Comments
Mega	50 to 100+ MWe	Very large industrial Usually multiple smaller units Custom engineered systems
Large	10s of MWe	Industrial and large commercial Usually multiple smaller units Custom engineered systems
Mid	10s of kWe to Several MWe	Commercial and light industrial Single to multiple units Potential packaged units
Micro	<60 kWe	Small commercial and residential Appliance-like

more so than on others when a load following operational strategy is used. A reciprocating engine generator responds much better to changing loads than a gas turbine does, not only in terms of efficiency, but also reliability. Steam turbines can match loads well by simply throttling the steam flow through the turbine.

An important consideration when choosing a cogeneration system is what type of fuel is most readily available. For almost every fuel, there is a system capable of using it. Gaseous fuel, such as natural gas, is most commonly used in gas turbines, but it is also used in natural gas fired reciprocating engines. Fuels such as No. 2 and No. 6 oils are burned in reciprocating engines, and No. 2 oil is used as a backup fuel for gas turbines. Solid fuels, such as coal and biomass, are exclusively used in the Rankine cycle. Except for the solid fuels, any fuel can be used in any system, so a certain amount of flexibility exists. However, using a fuel other than the ideal will cause increased operating costs and decreased equipment life.

The type of industry choosing to cogenerate will often determine the fuel, and thereby cogeneration system to be used. The paper industry, which generates a great deal of biomass and chemical by product fuel, generally opts for a Rankine cycle system to utilize the readily available fuel source. The huge boilers burn both bark removed from the incoming logs and chemical liquor generated in the pulp making process. Similarly, the petroleum industry most often relies on fuel oil as a heat source. Because of the available supply and low cost associated with using one's own fuel oil, it makes excellent economic sense to do so. However, for those industries that do not generate a fuel source in their production process, natural gas is often the best choice, due to the low cost, high efficiency, ease of transport, and low capital cost of the storage and distribution equipment (Bretton 1997).

Pollution concerns have become particularly important in recent years, especially in heavily populated areas. Gaseous fuels tend to have the lowest emissions, followed by fuel oils, and finally solid fuels. However, in large industrial locations using solid fuels, exhaust stacks are equipped with scrubbers or precipitators to remove particulate matter or other pollutants from exhaust, thus minimizing pollution concerns. It should be borne in mind that these scrubbers add considerable cost to the overall system, and any economic analysis should include the additional capital outlay. Heavier grade fuel oils can have a high sulfur content, and unless special steps are taken, sulfur emissions can be considerable. Low sulfur oils are available, but again at a higher cost. Finally, the efficient operation of each of the systems will minimize the pollutants generated in the combustion process. If the combustion process for any of the systems is poorly managed (through combustion air, *etc.*), or maintenance is not performed at required intervals, pollutants can increase dramatically.

The physical space available for a cogeneration system will often affect which type of equipment is used. Gas turbines and reciprocating engine generators are compact, packaged units which are simply dropped into place, attached to the fuel, steam, and electrical systems, and started. Steam turbine systems usually require more on-site preparation, but only because "drop-in" packaged units do not exist. For completely new systems, steam turbine cogeneration systems are the most

expensive, due to the high cost of the boilers, condensers, and other associated equipment required for operation.

The operational cost is a key factor in choosing a cogeneration system. Systems that have high fuel, maintenance, or supervisory costs will undermine any savings gained from cogenerating. Generally speaking, reciprocating engine generators have the highest operating costs, in terms of downtime and preventive maintenance, due to the high number of moving parts in the system. Steam turbine systems have lower maintenance costs than reciprocating engines, with gas turbines having the lowest costs of all.

Some general guidelines have been developed through experience with regard to selecting a prime mover (Dyer 1991). Specifically, reciprocating engines, micro gas turbines, and fuel cells tend to prosper in smaller systems (micro and mid systems), up to 3,000 kW, or systems where a peak shaving operational strategy is used (because of the relatively short operational time). Gas turbines perform best in moderately larger applications (med and large systems), from approximately 5,000 kW up to several hundred MW. Steam turbines are ideal for the largest applications (large and mega systems) or applications where solid fuel is used, because the large boilers that use this type of fuel produce enough steam to allow for huge extraction turbines to produce sizable amounts of electricity. Steam turbines will also perform well in any situation in which steam is required at different pressures.

1.5 Cogeneration Fuel Cells – Sorption Air Conditioning Systems

1.5.1 Trigeneration

The simultaneous use of energy allows one to achieve high levels of energy efficiency, lower CO_2 emissions, a security of supply, as well as lower losses. Cogeneration is among different kinds of technologies that allow the waste heat utilization for power generation, where electricity and heat are produced simultaneously. If some cooling type is required and this is produced by the same energy source, this process is known as trigeneration (electricity, heat, and cold). Figure 1.4 shows a trigeneration system schematically.

The trigeneration process increases the energy efficiency due to better utilization of waste heat into cooling power. If sorption refrigeration systems are integrated the environmental impact is reduced due to the use of natural refrigerants (ammonia, water, methylamine, ammonium nitrate, alcohol, etc.) The trigeneration plant can be evaluated as a cogeneration plant, considering all the heat used in producing cold.

This cooling can be done through sorption (absorption or adsorption refrigeration) cycles. These systems are adapted in order to recover industrial and commercial waste heat, hot liquid or hot gas, and steam, to provide cold for air condi-

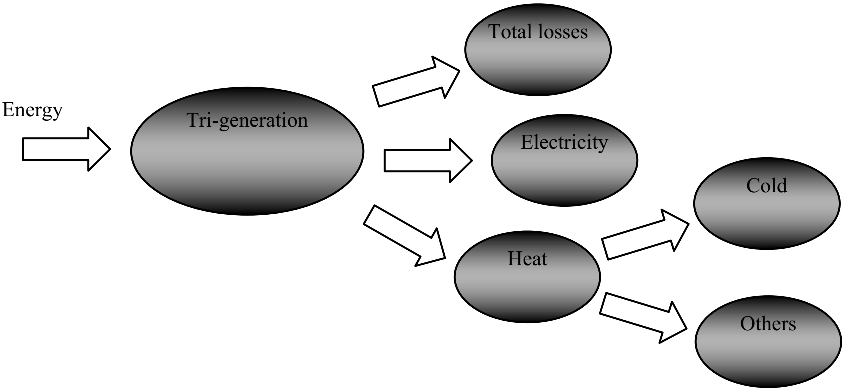

Figure 1.4 A trigeneration system

tioning or low temperature processes, as it is possible to achieve high rates of performance using residual thermal flows at relatively low temperature.

These sorption systems can be operated with thermal residual flows with a temperature range from 60–80 °C and low pressure steam, or up to 150 °C, if a double effect configuration is considered. In the case of gaseous flow, we need minimum temperatures of the order of 250 °C, due to the need for intermediate heat exchange circuit in order to generate hot water at a temperature up to 120 °C.

To generate cooling power for air conditioning application using sorption refrigeration cycles, a heat source with a temperature range between 80–200 ºC (single and double effect) is required, depending on the technology selected.

1.5.2 Fuel Cells in the Trigeneration Process

The fuel cell is a technology with good performance when integrated into a trigeneration generation process. The chemical energy is transformed into electricity, heat, and water. These devices have high efficiency, low emission and noise, and a modular design. Their main practical applications are in the transport sector. Fuel cells are classified by the electrolyte used and the operating temperature. Molten carbonate (MC) and solid oxide (SO) fuel cells correspond to high temperature technology (650–1050 °C) and the proton exchange membrane (PEM) and direct methanol (DM) to low temperature technology (60–250 °C). The combined use of electricity and heat produced by the electrochemical reactions gives a high overall performance of 85 %. In order to optimize the efficiency of these devices, various projects are being carried out for the use waste heat for air conditioning systems in residential, commercial, and industrial sectors.

The waste heat released by a PEM fuel cell enables one to obtain hot water with temperatures up to 80 °C, which is suitable for the operation of sorption refrigeration cycles.

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